Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis

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ABSTRACT

Renewable energy consumption has been promoted to mitigate climate change problems under various schemes, such as the Kyoto Protocol and the Paris Agreement. A country's choice of energy resources depends on the balancing of economic growth and environmental degradation, which will be closely related to its development stage. This study examines how the relationship between renewable energy consumption and carbon emissions is associated with the development stage by applying a panel cointegration analysis to 107 countries during the period from 1990 to 2013. The analysis shows the clear differences between the groups of low- and high-income countries. For low-income countries, renewable energy consumption is positively and negatively associated with carbon emissions and output, respectively. However, for high-income countries, renewable energy consumption is negatively and positively associated with carbon emissions and output, respectively. These results have important implications for policymakers, since the discrepancies in these relationships mean that a country's renewable energy policies should be highly compatible with its development stage.

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1. Introduction

Economic development has been accompanied by the use of a tremendous amount of energy, so that the majority of countries, particularly developing and emerging countries in recent decades, have increased their greenhouse gas emissions. This fact has intensified problems concerning global climate change, polluted environments, and energy security, leading to the establishment of the Kyoto Protocol and the Paris Agreement to commit state parties to reduce greenhouse gas emissions. In the Paris Agreement, each country determines, plans, and reports its own contribution to mitigating global warming. Central authorities of each country have been encouraged or enforced to reconsider energy policies, including the composition of energy production and consumption and the shift toward clean or renewable energy. In addition, with concerns about the future exhaustion of non-renewable energy sources such as coal and oil, energy price fluctuations and geopolitical disputation involving fossil fuels exploitation have stimulated the usage of renewable energy [1].

Numerous studies and policy reports emphasize indispensable and crucial roles of non-fossil fuels, including solar, wind, biofuel, tides, waves, and geothermal heat, in diversifying energy supply sources and mitigating environmental and energy issues [2—5]. Renewable energy consumption is still limited, in spite of having an upward trend, due to its relatively high costs and technological barriers in many countries, while non-renewable energy consumption has been increasing considerably in comparison due mainly to its relatively low costs and ease of operation. The report of the International Energy Agency (IEA) [6] shows that renewable energy sources provided the global market with a share of only 13.8% of the total energy supply in 2014, among which biofuels and waste accounted for 72.8%, followed by 17.7% hydro and 3.8% geothermal energy.

To highlight the indispensable roles of renewable and clean energy, the environmental Kuznets curve (EKC) hypothesis postulates that in the early stages of economic development, the environmental quality is degraded because of the industrialization processes, the increasing exploitation of fossil fuels, and output expansion (see, e.g., Refs [7,8]). Nonetheless, in the later stages of economic development, people tend to be more concerned about environmental pollution, which in turn leads to remarkable decreases in the environmental deterioration with increasing use of

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clean energy and new innovative green technologies. Indeed, several researchers have found a favorable linkage between renewable energy consumption and economic growth [9–11]. Given the arguments that renewable energy is environmentally friendly and that its importance depends on a country's development stage, this study attempts to empirically investigate how the development stage relates to the association between renewable energy consumption and carbon emissions. The examination of such an issue would enable us to draw some important lessons for planning and adopting renewable energy policy, particularly in developing countries that will face increased energy demands during their development process.

The intensified role of renewable energy associated with environmental concerns has inspired much attention in the literature to empirically explore the linkage of renewable energy consumption with pollutant emissions, particularly carbon emissions, and output growth. Although several studies examine such an issue, they focus on specific country groups, such as the G7 and emerging countries. In contrast to the previous studies, this study attempts to investigate how the long-term relevance of renewable and non-renewable energy demands with carbon emissions and output would depend on countries' development stage. To do so, we apply panel cointegration methods, including the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) estimators, to comprehensive panel data for 107 countries in the world during the period of 1990—2013. The sample countries are classified into three income groups: low-, middle-, and high-income groups, which will enable us to capture how development stages relate to the long-run relationships among variables and to confirm their discrepancies among the different income groups.

The results show that the long-run of renewable energy consumption with carbon emissions depends on countries' income level, i.e., the development stage. Renewable energy consumption is negatively associated with carbon emissions for high-income countries, while the relationship is opposite for low-income countries. The analysis also finds that the relationship between renewable energy consumption and output depends on countries' development stage. Renewable energy consumption is positively correlated with output for high-income countries, while the relationship is opposite for low-income countries. Our results support the argument of the EKC and confirm ongoing concerns about environmental quality at the early stages of economic development. At the early stages of development, economic growth would reduce (increase) the portion of renewable (non-renewable) energy and thus increase carbon emissions. In contrast, at the later stages of development, economic growth would increase the portion of renewable energy significantly and thus decrease carbon emissions. Regulators should adopt flexible and effective energy strategies, such as tax exemption, renewable energy subsidies, and higher environmental taxes for CO_2 emissions, to initiate the independence from fossil fuels as well as stimulate investment and development in sustainable energy supply.

The remainder of this study is organized as follows. Section 2 presents a literature review. Section 3 first describes data and methodology used in this study. Then, we present the empirical results of our analysis, including panel unit root tests, panel cointegration tests, and the long-run estimates under the FMOLS and DOLS methods and discuss some implications derived from our empirical results. The final section provides our conclusions.

2. Literature review

Various studies in the energy economics literature have extensively discussed the link between renewable energy consumption and output or income. To examine this relationship, there are two

primary approaches: supply-side and demand-side. Specifically, the supply-side approach tends to highlight the vital role of renewable energy consumption combined with capital and labor in an economy under a production framework, while the demand-side approach tends to underline the key role of output and energy prices on the consumption of renewable energy under the model of energy demand.[1] The past studies of the supply-side approach, including Aiisa, Jebli, and Youssef [18], generally confirm the positive link of renewable energy consumption to economic growth. On the other hand, some empirical studies in the context of the demand-side approach, such as Apergis and Payne [19,20], determine the long-run relationship among renewable energy consumption, output, carbon emissions, and oil price, and most studies suggest that renewable energy consumption has a positive long-run association with output and CO_2 emissions, but a small or negative long-run association with oil price.

Recently, several empirical studies have discussed the long-run role of renewable energy consumption in relation to macroeconomic conditions by applying panel cointegration analysis, mainly using the FMOLS and DOLS.[2] For example, Sadorsky [10] investigates the relationship among renewable energy consumption, income, and electricity prices in emerging countries during the period of 1994—2003 and shows the positive long-run association of income and electricity prices with renewable energy consumption. Likewise, Sadorsky [11] also examines the long-run properties of renewable energy consumption in the G7 countries during the period of 1980—2005 and demonstrates that real output and carbon emissions are key determinants of renewable energy consumption, while oil prices have a small and negative impact on renewables. Similarly, the work of Salim and Rafiq [17] on six emerging countries (Brazil, China, India, Indonesia, Philippines, and Turkey) during the period of 1980—2006 indicates that income and carbon emissions are crucial in determining renewable energy consumption, while oil prices appear not to have any clear effects. Moreover, Apergis and Payne [20] explore the role of renewable energy consumption in 11 South American countries during the period of 1980—2010 and confirm that real GDP, CO_2 emissions, and real oil price have a positive long-run relationship with renewable energy consumption.

Applying different approaches from panel cointegration analysis, some studies explore the evidence showing the importance of renewable energy. For instance, Apergis and Payne [19] employ structural break analysis and nonlinear panel smooth transition vector error correction models and find a positive long-run association among real GDP, CO_2 emissions, and real oil price with renewable energy consumption in seven Central American countries during the period of 1980—2010. Omri and Nguyen [16] apply dynamic panel data analysis to identify determinants of renewable energy consumption in 64 countries during the period of 1990—2011 and reveal that CO_2 emissions are an important factor to promote renewable energy demand, while oil price has a negative impact only in middle income countries. In the literature, the importance of renewable energy to mitigate global environmental issues has inspired much attention to empirically examine the relationship among renewable energy consumption, pollutant emissions, particularly carbon emissions, and output growth. However, they have focused on some specific country groups, such as the G7 and emerging countries. Differently from the previous

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[1] The studies of the supply-side approach also include Refs. [1,3,9,12—15]. In addition, the works of the demand-side approach also include Refs. [10,11,16,17].

[2] Recently, the panel cointegration technique has been applied in a number of empirical works in various contexts, including the examination of the relationship between energy consumption and output (see, e.g., Refs. [9—12,18,21—30]).

studies, this study attempts to connect countries' development stage to the long-run relevance of renewable and non-renewable energy demands with carbon emissions and output.

3. Empirical analysis

3.1. Model specification and data

The empirical framework in this study follows the approach of Sadorsky [11] and Salim and Rafiq [17], originating mainly from the demand-side approach in which the demand for renewable energy is specified by output, carbon emissions, and the prices of renewable energy and its substitutes. The demand for renewable energy depends not only on the price of renewable energy but also the price of its substitute. Renewable energy is the combination of a wide range of sources such as wind, solar, geothermal, biofuels, biomass, tides, and waves, so it is generally difficult to identify the exact price. Although we admit this issue, we regard the oil price as a relative price of non-renewable energy to renewable energy, as in Refs. [11,17].

Our main interest in this study is on how the long-run association among renewable energy consumption, output, carbon emissions, and the oil price relates to countries' development stages. In this study, along with the demand for renewable energy, we also examine the demand for non-renewable energy. Specifically, we estimate the following two equations:

$$REC_{it} = \alpha_0 + \alpha_{i1}Y_{it} + \alpha_{i2}CO_{it} + \alpha_{i3}P_{it} + v_i + \varepsilon_{it} \tag{1}$$

$$NREC_{it} = \beta_0 + \beta_{i1}Y_{it} + \beta_{i2}CO_{it} + \beta_{i3}P_{it} + u_i + \varepsilon_{it} \tag{2}$$

where REC_{it}, $NREC_{it}$, Y_{it}, CO_{it}, and P_{it} stand for the logs of renewable energy consumption, non-renewable energy consumption, real output (real GDP), CO_2 emissions, and real oil price in country i at year t, respectively; v_i and u_i are country-specific fixed effects; and ε_{it} and ε_{it} are the error terms. Real GDP is measured as expenditure-side real GDP at chained PPPs (millions of 2011 US dollars), which is taken from the Penn World Tables (version 9.0). The data on renewable (non-renewable) energy consumption and carbon emissions is obtained from the International Energy Agency (IEA). Renewable energy consumption is captured by the total renewable energy consumption (kilotons of oil equivalent (ktoe)), including geothermal, solar, wind, biofuels, and biomass electric power consumption, and non-renewable energy consumption is calculated as the total energy consumption minus renewable energy consumption (ktoe). Carbon emissions are measured by CO_2 emissions (ktoe). The oil price is measured by the spot price of West Texas Intermediate (WTI), which is taken from the British Petroleum Statistical Review of World Energy. We transform it into the real oil price by using exchange rates and the US and domestic GDP deflators.

For the renewable energy consumption equation, real GDP and CO_2 emissions are expected to show a positive relationship with non-renewable energy consumption, while the oil price should show the inverse relationship. On the other hand, the prediction of

the long-run association for the renewable energy consumption equation might rely significantly on the development stage. Thus, we address this issue by dividing our full sample into three income groups: high-, middle-, and low-income groups (Table 1). The sample covers 107 countries during the period from 1990 to 2013. This study assigns the three income groups based on the World Bank's income classification.[3] Low- and lower middle-income countries under the World Bank classification are classified as one group, namely, the low-income group. In addition, upper middle- and high-income countries under the World Bank classification correspond to middle- and high-income groups in our study, respectively. Table 2 presents the summary statistics of variables used in our analysis.

To evaluate the association of renewable (non-renewable) energy consumption with real GDP, CO_2 emissions, and oil price for each income group, this study employs the panel cointegration technique. Recently, this technique has been applied by a number of empirical works in various contexts. The analysis of cross-sections of time series is more efficient with high degrees of freedom than individual time series, particularly in the case where the time series dimension of each cross-section is relatively short. Following the works of Sadorsky [10,11] and Aïssa, Jebli, and Youssef [18] on renewable energy consumption, this study estimates long-run elasticities in the renewable and non-renewable energy consumption equations (1) and (2) by applying the panel cointegration methods of Pedroni [32,33]. As in most of the time series literature, this study first conducts stationarity tests and panel cointegration tests and then evaluates the long-run relationships.

3.2. Stationarity tests

With the panel data, we need to check the stationarity of the variables to make sure that they fluctuate around a constant mean, since running regression models with nonstationary variables often leads to unreliable results. To check the stationarity of variables, this study conducts five types of panel unit root tests, i.e., Levin-Lin-Chu, Breitung, Im-Pesaran-Shin, Fisher-ADF, and Fisher-PP tests.[4] All the tests employ a null hypothesis of a unit root. Table 3 presents the results of the panel unit root tests on variables used in this study (REC, NREC, Y, CO_2, and P) for each income group. The test results confirm that in general, all variables are non-stationary at the level but stationary at the first-difference, i.e., they are integrated of order one, I(1).

3.3. Cointegration tests

Once we confirm that all variables are stationary at the first-difference, the next step is to examine the existence of the long-run relationships among the variables. This study applies two panel cointegration tests developed by Pedroni [41,42] and Kao [43], which extend the Engle-Granger [44] two-step residual-based cointegration tests. In this study, all variables in the renewable and non-renewable energy consumption equations (1) and (2) are integrated of order one, as shown in the previous subsection. Pedroni [41,42] proposes several tests for cointegration that allow for heterogeneous intercepts and trend coefficients across cross-sections. The Pedroni approach is to test whether the residual, e_{it}, derived from equations (1) and (2) has a unit root, where $e_{it} = \rho_i e_{it-1} + u_{it}$.

Table 1
List of sample countries.

Low-income countries (41)	Middle-income countries (31)	High-income countries (35)
Armenia	Angola	Australia
Bangladesh	Albania	Austria
Benin	Azerbaijan	Belgium
Bolivia	Belarus	Canada
Côte d'Ivoire	Bulgaria	Switzerland
Cameroon	Brazil	Chile
Congo	China	Cyprus
Egypt	Colombia	Germany
Ethiopia	Costa Rica	Denmark
Ghana	Dominican Republic	Spain
Guatemala	Algeria	Estonia
Haiti	Ecuador	Finland
Honduras	Gabon	France
India	Georgia	United Kingdom
Indonesia	Islamic Republic of Iran	Greece
Kenya	Iraq	Hong Kong
Kyrgyzstan	Jamaica	Hungary
Moldova	Jordan	Ireland
Mongolia	Kazakhstan	Iceland
Morocco	Lebanon	Israel
Mozambique	Mexico	Italy
Myanmar	Mauritius	Japan
Nepal	Malaysia	Korea
Nigeria	Panama	Latvia
Nicaragua	Peru	Lithuania
Pakistan	Paraguay	Netherlands
Philippines	Russian Federation	Norway
Senegal	Thailand	New Zealand
Sri Lanka	Turkey	Poland
El Savaldor	Turkmenistan	Portugal
Sudan	Venezuela	Saudi Arabia
Syrian Arab Republic		Sweden
Tanzania		Trinidad and Tobago
Togo		Uruguay
Tunisia		United States
Ukraine		
Uzbekistan		
Vietnam		
Yemen		
Zambia		
Zimbabwe		

Table 2
Descriptive statistics.

Variable	Obs	Mean	Std.Dev.	Min	Max
Low-income countries					
REC	984	7.342	2.529	0.731	12.053
NREC	984	8.101	1.587	4.164	12.784
Y	984	10.855	1.453	8.129	15.664
CO2	984	2.345	1.365	−0.357	6.653
P	984	4.396	0.830	1.876	7.546
Middle-income countries					
REC	744	6.523	2.218	1.890	12.301
NREC	744	9.389	1.850	5.594	14.359
Y	744	11.691	1.679	9.012	16.528
CO2	744	2.923	1.771	−0.400	8.009
P	744	4.431	0.631	2.427	7.811
High-income countries					
REC	840	6.826	1.887	1.261	11.234
NREC	840	10.140	1.595	6.772	14.231
Y	840	12.555	1.649	8.967	16.605
CO2	840	3.660	1.569	0.315	7.756
P	840	3.953	0.575	2.731	5.547

The null hypothesis of no cointegration is rejected if the residual is stationary.

Pedroni [41,42] offers seven statistics (panel v-statistic, panel rho-statistic, panel PP-statistic, panel ADF-statistic, group rho-statistic, group PP-statistic, and group ADF-statistic) to test for the null hypothesis of $\rho_i = 1$. There are two alternative hypotheses. One is the homogenous alternative of $\rho_i = \rho < 1$ for all i, and the other is the heterogeneous alternative of $\rho_i < 1$ for all i. The former is referred to as the within-dimension or panel test, while the latter as the between-dimension or group test. The within-dimension test proposes a common autoregressive coefficient across cross-sections, while the between-dimension test assumes an individual autoregressive coefficient for each cross-section. It should be noted that the between-dimension tests are less restrictive since they do not require a common value of ρ under the alternative hypothesis, and they allow for heterogeneity of the parameters across cross-sections.

Tables 4 and 5 present the results of the Pedroni cointegration tests for the renewable and non-renewable energy consumption equations (1) and (2). For each income group, two or three statistics of the unweighted within-dimension and two statistics of the between-dimension tests show the significance for the renewable and non-renewable energy consumption equations. The results of the Pedroni panel cointegration tests reveal the existence of cointegration or a long-term relationship among renewable (non-renewable) energy consumption, real GDP, CO_2 emissions, and oil price.

As another approach, the panel cointegration test proposed by Kao [43] takes a similar approach as the Pedroni tests but requires cross-section specific intercepts and homogeneous coefficients on the regressors in the first stage estimation.[5] Conducting the Kao panel cointegration test should be useful for robustness checking to confirm the existence of cointegration deduced from the Pedroni tests. Tables 6 and 7 show the results of the Kao cointegration tests for the renewable and non-renewable energy consumption equations (1) and (2), which indicate that for each income group, the null hypothesis of no cointegration is rejected at the 1% or 5% significance level for both equations. This verifies that there exists a long-run relationship between renewable (non-renewable) energy consumption, real GDP, CO_2 emissions, and oil price for all income groups, which is consistent with the results of the Pedroni panel cointegration tests.

3.4. Long-run estimates

This subsection evaluates the long-run relationship among renewable (non-renewable) energy consumption, real GDP, CO_2 emissions, and oil price, following the works of Sadorsky [10,11] among others. The ordinary least squares (OLS) estimator is asymptotically biased, and its distribution depends on nuisance parameters; the nuisance parameters are regressors that are not part of the true data-generating process but can introduce undesirable endogeneity and serial correlation. To mitigate such problems, Pedroni [32,33] proposes a group-means fully modified OLS (FMOLS) estimator that incorporates a semiparametric correction to the OLS estimator to eliminate the endogeneity and serial correlation.[6] In addition to the FMOLS estimation, Pedroni [33] also proposes a parametric dynamic OLS (DOLS) estimator that parametrically corrects the OLS estimator to eliminate the endogeneity

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[5] Kao [43] investigates the asymptotic null distribution of residual-based cointegration test in panel data by applying Dickey-Fuller (DF) and augmented Dickey-Fuller (ADF) tests.

[6] Pedroni [32] mentions that the group-mean panel FMOLS method gives consistent point estimates of the sample mean, whereas the pooled panel FMOLS method does not give totally consistent point estimates when the true slope coefficients are heterogeneous.

Table 3
Panel unit root tests.

	Null: unit root								
	Levin, Lin, and Chu (LLC)		Breitung t-stat		Im, Persaran, and Shin (IPS) W-stat		ADF-Fisher Chi-square		PP- Fisher Chi-square	
Low-income countries									
REC	0.509	[0.695]	−0.317	[0.376]	8.354	[1.000]	50.565	[0.996]	67.705***	[0.841]
ΔREC	−30.786***	[0.000]	−12.976***	[0.000]	−28.748***	[0.000]	1059.43***	[0.000]	1048.11***	[0.000]
NREC	−0.209**	[0.289]	3.880	[0.999]	0.4731	[0.681]	86.904	[0.334]	66.681	[0.890]
ΔNREC	−18.011***	[0.000]	−10.774***	[0.000]	−19.239***	[0.000]	446.521***	[0.000]	838.413***	[0.000]
Y	4.650	[1.000]	3.042	[0.998]	12.316	[1.000]	19.615	[1.000]	17.748	[1.000]
ΔY	−10.572***	[0.000]	−7.422***	[0.000]	−10.564***	[0.000]	265.798***	[0.000]	342.159***	[0.000]
CO2	−0.703	[0.241]	3.488	[0.999]	1.151	[0.875]	91.589	[0.219]	76.817	[0.641]
ΔCO2	−17.222***	[0.000]	−7.581***	[0.000]	−16.097***	[0.000]	375.821***	[0.000]	773.284***	[0.000]
P	−0.404	[0.343]	2.043	[0.576]	4.615	[1.000]	35.953	[1.000]	32.862	[1.000]
ΔP	−23.057***	[0.000]	−18.910	[0.000]	−22.991***	[0.000]	575.498***	[0.000]	941.813***	[0.000]
Middle-income countries									
REC	0.406	[0.658]	0.505	[0.693]	3.234	[0.999]	41.973	[0.976]	49.248	[0.879]
ΔREC	−10.593***	[0.000]	−5.154***	[0.000]	−15.564***	[0.000]	320.781***	[0.000]	1036.09***	[0.000]
NREC	−0.534	[0.235]	2.056	[0.945]	5.584	[1.000]	31.987	[1.000]	35.502	[0.992]
ΔNREC	−15.518***	[0.000]	−8.855***	[0.000]	−15.547***	[0.000]	309.004***	[0.000]	349.193***	[0.000]
Y	−2.115	[0.017]	3.050	[0.998]	−0.663	[0.253]	17.263	[0.999]	25.181	[1.000]
ΔY	−18.349***	[0.000]	−9.227***	[0.000]	−14.609***	[0.000]	299.243***	[0.000]	266.423***	[0.000]
CO2	−1.031	[0.151]	5.672	[1.000]	2.092	[0.981]	72.359	[0.173]	77.578	[0.623]
ΔCO2	−15.754***	[0.000]	−9.679***	[0.000]	−15.776***	[0.000]	316.707***	[0.000]	534.519***	[0.000]
P	0.177	[0.571]	−0.265	[0.407]	2.365	[0.991]	52.099	[0.811]	51.353	[0.831]
ΔP	−18.085***	[0.000]	−15.355***	[0.000]	−15.321***	[0.000]	304.463***	[0.000]	690.551***	[0.000]
High-income countries									
REC	−0.770	[0.220]	0.952	[0.829]	0.154	[0.561]	77.388	[0.255]	76.595	[0.275]
ΔREC	−7.361***	[0.000]	−3.250***	[0.000]	−10.931***	[0.000]	253.234***	[0.000]	965.480***	[0.000]
NREC	−0.706	[0.240]	6.053	[1.000]	4.149	[1.000]	79.465	[0.206]	103.837	[0.005]
ΔNREC	−4.758***	[0.000]	−3.228***	[0.000]	−9.992***	[0.000]	240.129***	[0.000]	1048.98***	[0.000]
Y	−0.261	[0.343]	0.712	[0.761]	−0.652	[0.257]	22.414	[1.000]	66.252	[0.604]
ΔY	−6.592***	[0.000]	−6.133***	[0.000]	−7.164***	[0.000]	173.513***	[0.000]	365.438***	[0.000]
CO2	0.163	[0.565]	5.503	[1.000]	3.606	[0.999]	69.181	[0.505]	79.432	[0.550]
ΔCO2	−6.124***	[0.000]	−3.750***	[0.004]	−9.639***	[0.000]	221.551***	[0.000]	933.908***	[0.000]
P	2.0643	[0.980]	1.239	[0.998]	6.524	[1.000]	10.597	[1.000]	7.734	[1.000]
ΔP	−23.394***	[0.000]	−9.075***	[0.000]	−20.721***	[0.000]	480.449***	[0.000]	649.647***	[0.000]

Notes: (1) Figures in the parenthesis indicate p-values. (1) Optimal lag lengths are determined by Schwarz Info Criterion (SIC). (3) Individual intercept and individual linear trend are included. (4) *, **, and *** represent the 10%, 5%, and 1% significance levels, respectively.

and serial correlation (see, e.g., Ref [45] for a summary of the differences between these two estimators).[7] This study applies the two different estimation techniques, the group-mean FMOLS and DOLS estimations, to confirm the robustness of the estimated results. Given that all variables are in terms of natural logarithms, long-term elasticities can be represented by the estimated coefficients in the long-run cointegration equations. Table 8 demonstrates the estimated long-run elasticities of renewable (non-renewable) energy consumption with respect to real output and CO_2 emissions for each of the three income groups. Both the FMOLS and DOLS approaches generally show consistent results concerning the long-run relationship for the renewable (REC) and non-renewable (NREC) energy consumption equations.

Concerning the low-income group, renewable energy consumption has a negative relationship with real output, but a positive relationship with CO_2 emissions, while non-renewable energy consumption has a positive relationship with real output and CO_2 emissions. The larger coefficients of CO_2 emissions in the NREC equation compared to those in the REC equation reveal that non-renewable energy consumption is more sensitive to CO_2 emissions. On the other hand, for the high-income groups, the estimated long-run elasticities of renewable energy consumption show contrasting results to the case of the low-income group. Renewable energy consumption has a positive relationship with real output but a negative relationship with CO_2 emissions, while non-renewable energy consumption has a positive relationship with real output and CO_2 emissions. The estimated coefficients of real output in the REC equation are larger than those in the NREC equation, which implies that renewable energy consumption is more sensitive to real output. Regarding the middle-income group, the estimated coefficients are qualitatively similar to those for the high-income group, but their values are different. In the REC equation, the estimated coefficients of real output and CO_2 emissions for the middle-income group are between those for the low- and high-income groups. In the NREC equation, the coefficients of CO_2 emissions for the middle-income group are between those for the low- and high-income groups, while those of real output for the middle-income group are the lowest among all income groups.

The comparison of the results between the low- and high-income groups clarifies some differences in the estimated elasticities in response to real output and CO_2 emissions. First, renewable energy consumption tends to have a negative and positive relationship with real output in low- and high-income countries,

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[7] Harris and Sollis [45] mention a choice problem on how the data are pooled. Pooling can be based on either within- or between-dimension, where the former estimator assumes a common regression coefficient vector across all cross-sections, while the latter or group means estimator allows the regression coefficients to vary across cross-sections. Moreover, DOLS and FMOLS should derive similar parameter estimates asymptotically, although it is not clear which approach works better in small sample cases (see Refs. [29,30]). Furthermore, Kao and Chiang [46] argue that the FMOLS estimator does not overcome the bias of OLS in general, while the DOLS estimator provides the least bias compared with OLS and FMOLS methods. Stock and Watson [47] suggest that DOLS are likely to be applicable for variables integrated of alternative orders (a higher order of integration), particularly in small samples. They perform both FMOLS and DOLS regressions by the group-mean method to avoid providing biased conclusions in some specific cases.

Table 4
Pedroni panel cointegration tests: Renewable energy consumption equation.

	Within dimension (panel statistics)			Between dimension (individual statistics)		
	Test	Statistics	Probability	Test	Statistics	Probability
Low-income countries						
Pedroni (1999)	Panel v-statistic	1.184	0.118	Group ρ Statistics	2.941	0.988
	Panel ρ-statistic	1.246	0.893	Group pp Statistics	−7.662***	0.000
	Panel PP-statistic	−4.467***	0.000	Group ADF Statistics	−7.196***	0.000
	Panel ADF-statistic	−4.204***	0.000			
Pedroni (2004) Weighted statistic	Panel v-statistic	2.882***	0.002			
	Panel ρ-statistic	0.344	0.634			
	Panel PP-statistic	−7.262***	0.000			
	Panel ADF-statistic	−6.812***	0.000			
Middle-income countries						
Pedroni (1999)	Panel v-statistic	−1.419	0.922	Group ρ Statistics	3.845	0.999
	Panel ρ-statistic	1.927	0.973	Group pp Statistics	−4.478***	0.000
	Panel PP-statistic	−3.031***	0.001	Group ADF Statistics	−4.827***	0.000
	Panel ADF-statistic	−3.028***	0.001			
Pedroni (2004) Weighted statistic	Panel v-statistic	0.188	0.425			
	Panel ρ-statistic	2.494	0.993			
	Panel PP-statistic	−1.944**	0.025			
	Panel ADF-statistic	−3.699***	0.000			
High-income countries						
Pedroni (1999)	Panel v-statistic	0.371	0.355	Group ρ Statistics	3.596	0.999
	Panel ρ-statistic	2.455	0.993	Group pp Statistics	−3.835***	0.000
	Panel PP-statistic	−1.588*	0.056	Group ADF Statistics	−5.501***	0.000
	Panel ADF-statistic	−6.977***	0.000			
Pedroni (2004) Weighted statistic	Panel v-statistic	−2.030	0.978			
	Panel ρ-statistic	1.669	0.952			
	Panel PP-statistic	−4.275***	0.000			
	Panel ADF-statistic	−6.389***	0.000			

Notes: Optimal lag lengths are determined by Schwarz Info Criterion (SIC). Individual intercept and individual linear trend are included in the test regressions. *, **, and *** represent the 10%, 5% and1% significance, respectively.

Table 5
Pedroni panel cointegration tests: Non-renewable energy consumption equation.

	Within dimension (panel statistics)			Between dimension (individual statistics)		
	Test	Statistics	Probability	Test	Statistics	Probability
Low-income countries						
Pedroni (1999)	Panel v-statistic	1.729**	0.042	Group ρ Statistics	3.327	0.999
	Panel ρ-statistic	1.711	0.956	Group pp Statistics	−5.219***	0.000
	Panel PP-statistic	−3.403***	0.000	Group ADF Statistics	−8.697***	0.000
	Panel ADF-statistic	−7.214***	0.000			
Pedroni (2004) Weighted statistic	Panel v-statistic	1.611*	0.053			
	Panel ρ-statistic	1.204	0.885			
	Panel PP-statistic	−5.647***	0.000			
	Panel ADF-statistic	−9.859***	0.000			
Middle-income countries						
Pedroni (1999)	Panel v-statistic	0.675	0.249	Group ρ Statistics	4.213	1.000
	Panel ρ-statistic	2.027	0.978	Group pp Statistics	−2.209**	0.013
	Panel PP-statistic	−2.291**	0.011	Group ADF Statistics	−2.251**	0.012
	Panel ADF-statistic	−1.606*	0.054			
Pedroni (2004) Weighted statistic	Panel v-statistic	1.559*	0.059			
	Panel ρ-statistic	2.801	0.997			
	Panel PP-statistic	−2.030*	0.087			
	Panel ADF-statistic	−1.011	0.156			
High-income countries						
Pedroni (1999)	Panel v-statistic	11.072***	0.000	Group ρ Statistics	4.027	1.000
	Panel ρ-statistic	2.091	0.981	Group pp Statistics	−3.433***	0.000
	Panel PP-statistic	−2.133**	0.016	Group ADF Statistics	−4.090***	0.000
	Panel ADF-statistic	−2.834***	0.002			
Pedroni (2004) Weighted statistic	Panel v-statistic	10.769***	0.000			
	Panel ρ-statistic	2.163	0.984			
	Panel PP-statistic	−2.325***	0.001			
	Panel ADF-statistic	−3.782***	0.000			

Notes: Optimal lag lengths are determined by Schwarz Info Criterion (SIC). Individual intercept and individual linear trend are included in the test regressions. *, **, and *** represent the 10%, 5% and1% significance, respectively.

respectively. Our results for the low-income group are in contrast to the works of Salim and Rafiq [17] and Sadorsky [10,11], but those for the high-income group are consistent with these works, which confirm the long-run positive relationship between renewable energy demand and real GDP in emerging economies and the G7 countries. A possible explanation is as follows. In less-developed countries, the lack of modern and affordable forms of energy decreases economic productivity and opportunities for income

Table 6
Kao panel cointegration tests: Renewable energy.

	Statistic	P-value
Low-income countries		
ADF	2.255**	0.012
Residual variance	0.007	
HAC variance	0.008	
Middle-income countries		
ADF	−1.819**	0.034
Residual variance	0.032	
HAC variance	0.031	
High-income countries		
ADF	−2.596***	0.004
Residual variance	0.018	
HAC variance	0.022	

Notes: *, **, and *** represent the 10%, 5% and 1% significance, respectively.

Table 7
Kao panel cointegration tests: Non-renewable energy.

	Statistic	P-value
Low-income countries		
ADF	−5.048***	0.000
Residual variance	0.003	
HAC variance	0.003	
Middle-income countries		
ADF	−1.752**	0.039
Residual variance	0.011	
HAC variance	0.013	
High-income countries		
ADF	−3.801***	0.000
Residual variance	0.002	
HAC variance	0.003	

Notes: *, **, and *** represent the 10%, 5% and 1% significance, respectively.

Table 8
Long-run estimates (FMOLS and DOLS).

	REC		NREC	
	FMOLS	DOLS	FMOLS	DOLS
Low income countries				
Y	−0.0350***	−0.0156**	0.4346***	0.3598***
CO_2	0.3369***	0.4292***	1.1268***	1.2080***
P	0.0755***	0.0202	−0.0860***	−0.0785**
Middle income countries				
Y	0.4665***	0.4056***	0.0338*	0.0520**
CO_2	−0.3598***	−0.3759**	1.1646***	1.0680***
P	−0.0723	−0.0103	−0.0277***	−0.0309**
High income countries				
Y	0.7092***	0.7926***	0.0531***	0.0749***
CO_2	−0.4797***	−0.5788*	0.9312***	0.9321***
P	0.0853***	0.1161*	−0.0196**	−0.0429***

Notes: *, **, and *** represent the 10%, 5% and 1% significance, respectively.

generation, so that they cannot afford to pay for the promotion of cleaner energy [48]. In addition, renewable energy projects tend to require advanced technology with relatively high costs, which must be a huge burden for national budgets. Moreover, in some low-income countries, the infrastructure for non-renewable energy already exists, and thus, most manufacturing operations and residents' daily activities are primarily based on non-renewable energy. Thus, it is still not feasible in some low-income countries to extensively use renewable energy, and governments often put their priorities on development agendas, such as growth promotion, poverty reduction, and infrastructure development, rather than the promotion of renewable energy. In contrast, in high-income countries, renewable-related projects have been encouraged by various energy policies, which are supported by the environment-

conscious public. Given the above arguments, low-income countries would have a negative relationship between renewable energy consumption and real output, while high-income countries would involve a positive relationship between the same variables.

The second difference between the low- and high-income groups is that low-income countries have a positive relationship between renewable energy consumption and CO_2 emissions, while high-income countries have a negative relationship. Our results showing the positive relationship for the low-income group coincide with the works of Sadorsky [11] and Salim and Rafiq [17]. However, the results of the negative relationship for the high-income group are inconsistent with the works of Sadorsky [11] and Salim and Rafiq [17]. Identifying how renewable energy consumption relates to CO_2 emissions is a debatable issue. Large CO_2 emissions enhance the desire for a cleaner environment and the usage of renewable energy, as emphasized in Omri and Nguyen [16]. This argument suggests that renewable energy consumption is expected to have a positive relationship with CO_2 emissions. On the other hand, the prevalence of renewable energy with green technology mitigates environmental problems of carbon emissions, which implies the negative association of renewable energy consumption and CO_2 emissions. Thus, the balancing of the positive and negative links determines the long-run relationship between them. Given the argument that renewable energy and the adoption of green technology tend to be more emphasized and prevalent in advanced countries, the negative relationship dominates the positive relationship in high-income countries, but it is dominated by the positive relationship in low-income countries.

Table 8 also presents price elasticities of the renewable and non-renewable energy demand. Price elasticities of renewable energy demand are significantly positive for the low- and high-income countries, while they are insignificant for the middle-income countries. These results suggest that a rise in oil price would increase renewable energy demand, i.e., the substitutability effect, for low- and high-income countries, but they show no clear evidence of the substitutability effect for middle-income countries. Such a substitutability effect is verified by various studies [11,17,19,20]. In addition, oil price has a negative relationship with non-renewable energy consumption, so that a rise in oil price leads to the decline in non-renewable energy demand. The long-run elasticities of non-renewable energy demand with respect to oil price (own-price elasticities) are much larger for the low-income group than for the high-income group, and those for the middle- and high-income groups have similar values. These results are as expected, since low-income countries rely largely on non-renewable energy, rather than renewable energy, for production and consumption.

Overall, our empirical analysis demonstrates that the long-term elasticities of renewable and non-renewable energy consumption with respect to real GDP, CO_2 emissions, and oil price depend on the development stage. Interestingly, our results end up advocating the validity of the EKC hypothesis. In the early stages of economic development, total energy consumption increases, as real GDP increases and economic development proceeds. When we consider the energy allocation, our analysis finds that low-income countries at the early stages of development face a decline in renewable energy consumption and substantial increase in non-renewable energy consumption. As a result, environmental quality is deteriorated seriously due to carbon emissions from fossil fuels exploitation. Notwithstanding, in the later stages of economic development, environmental pollution becomes a significant concern by governments and the general population. Thus, as real GDP increases, renewable energy consumption increases significantly compared to non-renewable energy consumption. With the prevalence of more environmental-friendly energy with green technology, environmental deterioration issues could be resolved.

4. Conclusion

Human societies have been suffering from severe environmental degradation by utilizing fossil fuels in the process of economic growth. To confirm the role of renewable energy in mitigating environmental problems, such as global warming and exhausted non-renewables, this study has shed light on how a country's development stage relates to the long-run relevance of renewable and non-renewable energy consumption with output and carbon emissions. We have employed a panel cointegration analysis with the FMOLS and DOLS estimates to a panel of 107 countries divided into three income groups (low-, middle-, and high-income groups) during the sample period of 1990–2013. The analysis has shown that renewable energy consumption is positively associated with carbon emissions and negatively associated with output for low-income countries, but the relationships are opposite for high-income countries. Our results would support the argument of the environmental Kuznets curve. At the early development stages, low-income countries use a large amount of non-renewable energy for economic growth, and consequently, the environment is seriously degraded due to large carbon emissions. On the other hand, at the later development stages, high-income countries emphasize the quality of the environment rather than economic growth by enhancing the usage of renewable energy, and consequently, carbon emissions decline considerably.

Our results provide important policy implications, since the development stage is a crucial factor relating to renewable and non-renewable energy demands. Less-developed countries at the early stages of development tend to prioritize economic growth or poverty reduction over environmental issues, which would increase non-renewable energy consumption and intensify environmental degradation. To mitigate environmental problems, particularly in less-developed countries, regulators should have effective and timely energy policies whose purpose is to escape much of the reliance on non-renewable energy by substituting clean and low-carbon energy sources for fossil fuels. To achieve this, there may be several energy policy options. First, regulators can highlight energy saving and conservation policies with an emphasis on the promotion of renewable energy. The national authorities identify the types of spearheaded renewables to focus on development effectively and economically. Less-developed countries may have a high potential to develop indigenous renewable energy resources by taking advantage of agricultural waste or products (e.g., rice husks, coffee residues, straight vegetable oil, sugarcane, sugar beet, soybean, and oil palm). With the aim of conservation energy, some large energy consumption sectors, such as industrial, transportation, and residential sectors, in less-developed countries are advised to utilize renewables so as to reduce the reliance on vulnerable energy systems and ensure energy security.

Second, it is essential for regulators to promulgate regulations related to prices or costs of renewable energy production and consumption (e.g., quota policies, feed-in-tariff policies, and subsidies policies) such that the regulations encourage individuals and firms to effectively substitute renewable energy for non-renewable energy. Third, governments can adopt support policies for both international and domestic investors to invest in renewable energy sectors by enacting legal frameworks as well as abolishing barriers related to administrative procedures, bureaucracies, and institutional constraints when entering into the energy markets. Simultaneously, governments can also continue financial supports in implementing experimental and official renewable energy projects through taxes exemption, preferential taxes, credit loans, and land lease. Furthermore, the international cooperation between developed and less-developed countries in the contexts of technology transfer, research and development (R&D), and human resources management can be promoted to support, expand, and stabilize renewable energy resources in less-developed countries. The emergent duties of governments are not only in reducing pollutant intensities but also in promoting renewable energy and the environmental awareness of the general public.

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